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Sensitivity of Important Western Conifer Species to SO2 and Seasonal Interaction of Acid Fog and Ozone

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Sensitivity of Important Western Conifer Species to SO_2 and Seasonal Interaction of Acid Fog and Ozone

W.E. Hogsett, David T. Tingey,
US EPA Environmental Research Laboratory
200 SW 35th Street
Corvallis, Oregon 97333

Craig Hendricks and Deborah Rossi
NSI Technology Services Corporation
US EPA Environmental Research Laboratory
200 SW 35th Street
Corvallis, Oregon 97333

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W.E. Hogsett,[1] David T. Tingey,[1] Craig Hendricks,[2] and Deborah Rossi[2]

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16. ABSTRACT

The increased concern for forest health and the role of anthropogenic deposition, including acidic/wet deposition and gaseous air pollutants, has led to the need to understand which forest species face the highest risk from atmospheric deposition. In order to address this issue for the Western U.S., a number of important western conifer species have been assessed with regard to seedling growth response to each of three different deposition scenarios likely to occur in the Western U.S. The exposure scenarios include (1) acid fog (fall-winter)/ozone (summer) in a seasonal interaction of each pollutant over the year, (2) acid fog only in fall-winter exposure, or (3) SO_2 gaseous pollutant over the fall and winter months. Seasonal occurrence of the pollutants, rather than concurrent pollutant combinations represent a realistic exposure scenario for much of the climatic conditions of the coastal Western U.S., and the Cascade and Sierra foothills. The fumigation regimes reflect the seasonality of deposition duration, frequency of events, and chemistry for fog; and the seasonality of the frequency and distribution parameters of O_3 and SO_2 characteristic of selected regions of the West. The fumigation periods are those months when these depositions occur primarily.

Five species were selected for study based on economic and ecological importance in the West. These included Douglas-fir, ponderosa pine, lodgepole pine, western hemlock, and western redcedar. Douglas-fir and ponderosa pine were screened at both ERL-C and the Forest Service Fire Lab at Riverside, California. A study similar to the one reported here has also been conducted at Riverside under the direction of Dr. Paul Miller. Seedling sensitivity was assessed as a growth response over two growing seasons, including the spring following the previous year's pollutant exposure. The various responses to the exposure scenarios for the first year's study are reported here. The study was repeated a second year, and these results are briefly discussed.

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INTRODUCTION:

The increased concern for forest health and the role of anthropogenic depositions, including acidic/wet deposition and gaseous air pollutants, has led to the need to understand which forest species face the highest risk from atmospheric deposition. In order to address this issue for the Western U.S., a number of important western conifer species have been assessed with regard to seedling growth response to each of three different deposition scenarios likely to occur in the Western U.S. The exposure scenarios include (1) acid fog (fall-winter)/ozone (summer) in a seasonal interaction of each pollutant over the year, (2) acid fog only in fall-winter exposure, or (3) SO_2 gaseous pollutant over the fall and winter months. Seasonal occurrence of the pollutants, rather than concurrent pollutant combinations represent a realistic exposure scenario for much of the climatic conditions of the coastal western U.S., and the Cascade and Sierra foothills. The fumigation regimes reflect the seasonality of deposition duration, frequency of events, and chemistry for fog; and the seasonality of the frequency and distribution parameters of O3 and SO_2 characteristic of selected regions of the West. The fumigation periods are those months when these depositions occur primarily.

Five species were selected for study based on economic and ecological importance in the West. These included Douglas-fir, ponderosa pine, lodgepole pine, western hemlock, and western redcedar. Douglas-fir and ponderosa pine were screened at both ERL-C and the Forest Service Fire Lab at Riverside, California. A study similar to the one reported here has also been conducted at Riverside under the direction of Dr. Paul Miller. Seedling sensitivity was assessed as a growth response over two growing seasons, including the spring following the previous year's pollutant exposure. The various responses to the exposure scenarios for the first year's study are reported here. The study was repeated a second year, and these results are briefly discussed.

METHODS:

Pollutant Exposure Regimes:

Pollutant exposures are conducted on a year-round schedule in modified open-top chambers [1] under natural environmental conditions employing simulated ambient exposure regimes for each of the pollutants. The exposure regimes were developed from regional ambient air quality data. The methods for construction of the individual pollutant exposure regimes follows.

Acid Fog -

The acidic fog exposure regimes were constructed from 'worst-case' ambient fog data for the purposes of a screening study. Construction of the simulated ambient exposure regimes for acidic fog involves selection of a fog chemistry (pH and ion

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concentration), as well as modeling the temporal dynamics of selected regional or site-specific fog events. Henninger Flats, California was selected as the site for the fog chemistry data, since this site had some of the most severe pH values for published fog analyses in the West [2]. The ion concentration of the pH 3.1 experimental treatment (Table I) is near the median ion concentrations for Henninger Flats and the pH is near the median pH of 2.9 for the site [2]. Additional experimental treatments (pH 2.1 and pH 5.6) were created by increasing or decreasing the ion concentrations, but keeping the nitrate-to-sulfate ratio approximately 2:1.(Table I). The pH 2.1 treatment represents the extreme value from the Henninger Flat site and the ionic concentrations for the pH 3.1 and 2.1 fog fall within the range of those observed at Henninger Flat [2]. The pH 5.6 fog is representative in ion concentrations for typical radiation-type fogs [3].

TABLE I. Ionic composition of acid fog treatments.

Component	pH 2.1	pH 3.1 (ueq/liter)	pH 5.6
H +	9610	1240	124
Na +	1080	570	130
K +	160	40	4
NH4 +	2360	590	59
Ca +2	150	150	15
Mg +2	840	210	21
Cl -	5040	210	21
NO3 -	5960	1490	149
SO4 -2	3200	800	80
OH -	0	300	153
Total Cations	14200	2800	353
Total Anions	14200	2500	250

Although the fog chemistry was available from some Western sites, no corresponding event frequency and duration data was available from these same monitoring sites for a sufficient time period to permit modeling the temporal dynamics of fog. Since the fog chemistry selected for the regimes represented what is perhaps a worst-case scenario, the coastal region of the Pacific Northwest (west of the Cascades and Sierras) was the source of event frequency and duration. The coastal regions have the highest frequency of occurrence on an annual basis of fog deposition within the West (greater than 60 days), and the preponderance of occurrences is in the winter months [4].

Two sites representative of this larger regional designation of the Coastal West where sufficient data were available were Portland and Eugene, Oregon. Hourly data of fog occurrence from 1948-1964 at these two city airport sites were obtained from Dr.

Kelly Redmond, Climatic Research Institute, Oregon State University. The data included visibility in miles recorded hourly and specific descriptions of meteorological events each hour, including fog. One kilometer was chosen as the visibility limit because it represents the international definition of fog [5]; however, other limits were employed for maximum visibility in the analysis for comparison of different fogs in the stochastic model. The limits included 1/8, 1/4, 1/2 and 1 mile, as well as 1 kilometer. The summary statistics derived for the Oregon data were similar to those for coastal regions through California and Washington [6].

The fog exposure regime (Fig. 1) was constructed with a stochastic simulation model using distribution functions that best described the three components of fog we chose to model for the regimes. The three components were (1) the hour of the day the visibility coincided with the definition of fog (start hour); (2) the duration of the fog; and (3) the length of time since the last fog event (gap length). For the two sites the summary statistics were similar. The analysis of the relationship of frequency of events and month of the year indicated a higher frequency of occurrence in the winter months. Consequently, only the winter months were used in the analysis.

The hour the fog event started was best described with a normal distribution with most of the observations occurring in the early morning hours. For each site the duration and gap length were best described with exponential functions, showing distinctly skewed distributions. The relationship between the three components indicated no correlation between gap and duration; a slightly negative correlation between gap and start hour (-.1); and a slightly positive correlation (+.1) between start hour and duration. Box-Jenkins type time series modeling of duration and gaps indicated these variables were best modeled as independent exponential events, independent of each other; and for this profile development, the start hour was also treated as a random, independent variable described with a normal distribution. A random variable model was used to generate simulated regimes for fog. In the model, both gaps and duration were assumed to be independent, identically distributed exponential random variables. The gaps were assumed to have a mean 3.1 days, so that they resemble the gaps at Portland and Eugene. The mean duration was assumed to be 4.2 hrs for the same reason. The start hour was modeled as a normal distribution with a mean of 4 a.m. and a standard deviation of 4 hours. Twenty-four simulations were generated and one was selected for generating a 60-day regime. The simulant selected had features that approximate the average for all the simulants. The regime is given in Fig. 1. Treatment levels have the same temporal regime, but with different pH value and their related ionic composition. The 60-day regimes are repeated as needed for the entire exposure period.

Ozone -

Finding sufficient hourly ozone monitoring data from rural and remote areas in the West was difficult, consequently the ozone exposure regimes were constructed from air quality data of the upper Midwest, including rural and remote sites in Minnesota, Wisconsin, and Michigan. The regimes, although constructed from upper Midwest data, are quite similar to hourly ozone concentrations and their temporal distributions observed from recent monitoring in the Cascades southeast of Seattle at Pack Forest, and the Sequoia National Park in California.

The exposure regimes were constructed averaging the following air quality characteristics over the 7 month period of April-October from 10 monitoring sites across the region: 1) frequency of occurrence of hourly concentrations in 0.01 ppm increments; 2) percentile distributions; 3) duration of concentrations; and 4) length of time between episodes or peak events [7,8]. These average values were then used to construct a 30-day hourly concentration regime that reflects the ambient air quality characteristics of the region (Fig. 2). The 30-day profile is repeated continuously over the designated exposure period or growing season. A range of treatments was created by increasing the hourly concentrations greater than or equal to 0.07 ppm by 60 and 80% (Fig. 2). The resulting regimes are within 1-2 standard deviations of the mean frequency of occurrence of concentrations from the regional mean values. A statistical summary of the three ozone treatments is given in Table II. The 7-hr mean is taken for the typical period of 9am-4pm and also the maximum 7-hr concentration period.

TABLE II. Seasonal statistical summary of ozone exposure profiles

Profile	7-hr mean (ppm)		12-hr mean (ppm)	30-day integrated sum (ppm-hr)		
	9am-4pm	11am-6pm	9am-9pm	>0	>.07	>.10
Base	0.053	0.055	0.050	27	5	1
Base*1.6	0.063	0.067	0.060	31	11	9
Base*1.8	0.067	0.071	0.064	34	14	12

Sulfur Dioxide -

The SO_2 exposure regimes were constructed from air quality data selected from the SAROAD database from sites in the West that represented worst-case scenarios for the point-source pollutant. All of the sites were associated with smelters and

were monitored for the years 1979-1983. Two Arizona sites (Gila and Greenlee Co.) had the most severe exposures and were selected to construct the profiles. Analysis and subsequent construction of the exposure regimes for gaseous SO_2 was handled differently than that for O_3. A stochastic modeling approach was used to more accurately describe the extreme fluctuations in concentrations that occur with a point-source pollutant (i.e. brief periods at high, extreme concentrations, and extended periods when the concentration is below or near the detection limit of the analyzer). The analysis involved modeling the components of the site air quality with time-series models, and then constructing an experimental exposure regime from the stochastic simulation model. The components of air quality that were modeled were 1) episode duration, 2) the time between episodes or gap length, 3) episode start time, 4) maximum concentration, 5) time of maximum concentration, 6) relationship of maximum concentration and episode duration, and 7) relationship of maximum concentration and hourly SO_2 concentration during that episode. The mathematical distributions of each of these components and their relationship to one another over time were determined.

The season when the highest concentrations occurred was during the winter months (December-February) at both sites. Since these higher values consistently occurred over all the years, only the winter months were used to construct the exposure profiles. An additional consideration in using only the winter months was the observation that at least some perennials exhibit increased sensitivity to SO_2 during the winter months [9]. Concentration of hourly SO_2 was analyzed in terms of episodes using a threshold value of 30 ppb and length of gap (i.e. time between episodes). Threshold values of 10, 60, 100, 150, and 250 ppb were also used, and the results were similar to those with 30 ppb. The distribution of maximum SO_2 concentration was also determined for the episodes. Finally the correlations between these three components, episode length, gap length, and episode maximum, was determined.

In addition to the above episode variables, the time variables of the air quality were also analyzed including start hour for the episode and the hour at which the maximum concentration occurs. The time variables at the two Arizona sites were different and probably reflected meteorological differences at the two locations. The start hour of an episode was more frequently around noon at Greenlee, however at Miami the start hour was not consistently at any particular hour across all hours. The time of day the maximum concentration occurred was midday at Greenlee and in the early morning hours at Miami.

The mathematical functions describing each of the above components of point-source air quality were used in a Box-Jenkins type time series model to generate a number of simulated exposure profiles. Twenty simulants were generated by the model and one was selected that had component characteristics which were about average for all the simulants, and this simulant rerun in the model with a 24 x 60 matrix generating the hourly SO_2

concentrations for a 60-day exposure profile. The base profile is shown in Figure 4. Additional treatments were created by reducing the concentration of all peaks in the base profile by 33% and 67%, and the event frequency of the base profile by 33% and 67% (Fig. 4). Table III gives a number of summary statistics for the SO_2 profiles.

TABLE III. Summary statistics for SO_2 exposure profiles

	Base	Base*0.67	Base*0.33
60-day mean (ppb)	65.78	42.18	20.93
60-day sum (ppb-h)	94716	60741	30135
Number Hrs > 30 ppb	369	318	270
Number Days 24 hr avg > 0.14 ppm	8	3	0
Number Days max 3-hr avg. > 0.50 ppm	12	4	0

Exposure Treatments:

The ozone exposure period in the first year's study (Table IV) was 134 days beginning 6/13/86 and the treatment levels included (1) 30-day sum of 31ppm and 7-hr x of 0.067 ppm (Fig. 2); 2) 30-day sum of 34 ppm and 7-hr x of 0.071 ppm (Fig. 2); and 3) charcoal-filtered air. Winter fog exposures followed the summer ozone exposure. Three fog treatment levels were employed and each had the same temporal regime (Fig. 1), but with different pH values, (5.6, 3.1, 2.1). Their related ionic compositions are given in Table I. The fog exposure period was for 60 days. The second deposition scenario of only acid fog employed the same fog exposure regimes as above, but with only 2 species, ponderosa pine and Douglas-fir, and no previous exposure to ozone (Table V). The third pollutant scenario was SO_2 exposures during the winter months (Table VI). Four treatment levels were employed (Fig. 3): 1) 66ppb 60-day mean; 2) 42ppb 60-day mean; 3) 21ppb 60-day mean; and 4) charcoal-filtered control.

Plant Culture:

Seedlings (1/0) of each species were obtained from commercial growers, and from known seed sources and regions. Douglas fir - Oregon seed zone 452 (2000 ft, western Cascades); western hemlock and western redcedar - Oregon seed zone 052 (Northern Coast Range); ponderosa pine - California seed zone 522 (2000 ft, western Sierra); lodgepole pine - Washington seed zone 821 (3500 ft, Colville National Forest). Seedlings were transplanted with minimum disturbance of the root ball to Dee-cells (2.5" x 10") in Pro-Mix[10]:Perlite (1:1 v/v) and supplied with a balanced nutrient at least 1 day/week, but not more than 2

days/week. Normal wet/dry cycles in soil moisture were maintained for optimal growing conditions.

Seedlings were selected from the whole population to increase the uniformity of the experimental population prior to beginning the study. The initial selection was based on seedling vigor and intact apical bud. From this resultant population, seedlings were selected based on stem diameter (approx. 1-2 mm range) primarily, and on height secondarily.

Design:

The experimental design for each of the exposure scenarios utilized a hierarchal structure with seedlings randomized to the chambers, stratified by pretreatment diameter. In the ozone/acid fog exposure study (Table IV), the ozone treatment levels were replicated three times, with 20 seedlings of each species in each chamber (60 seedlings per treatment); and following the ozone season all seedlings from each chamber were then randomly assigned to acid fog chambers. Each acid fog treatment was replicated twice, giving a total of 6 chambers with 20 plants per chamber. The other two pollutant scenarios, acid fog only or SO_2 only exposure, utilized the same design but with 20 seedlings of each species in each of two replicate chambers for a total of 40 seedlings per treatment (Table V & VI). After the appropriate exposure period, the seedlings were maintained in the nursery area for assessment of bud elongation and biomass the following spring/summer. The time of completion of bud elongation and spring growth varied among the five species. The experimental design was repeated in a second study (1987-1988), but the number of seedlings of each species assessed with each chamber replicate was increased from 20 to 24 with 3 chambers/treatment.

Two basic types of growth assessment are conducted during and following the different exposure periods: 1) Weekly or biweekly assessment of change in stem diameter and height on the same plants over the exposure periods ('repeated measurements'). Twenty seedlings/species/chamber; and 2) Final destructive harvests for assessment of changes in biomass and spring bud growth is conducted the spring/summer following the exposure periods. The variables include needle, stem, and root dry weight; number and length of branches; needle number by developmental stage; bud number and bud elongation. The final harvest utilized 10 plants/species/chamber for the ozone/acid fog exposure and 20 plants/species/chamber for the acid fog only and SO_2 only exposures.

A pretreatment harvest of 40 seedlings of each species preceded each of the three exposure studies to evaluate the relationship of pretreatment biomass (stem, needle, and root dry weight), and stem diameter and height. Pretreatment measurements of diameter and height of the experimental seedlings provided covariates for statistical analysis of the repeated measures data.

Analysis of variance or covariance was used to assess treatment effects. Table VII is an example of the parameters for analysis of variance for final harvest biomass variables. Transformations of the data were used due to nonconstant variances and nonadditivity. A natural log transformation was used for height, diameter, bud elongation, and dry weight variables. Proportion variables used an arcsin square root transformation, and count variables used a square-root transformation. With repeated measurements of stem height. diameter and bud elongation on the same plants, multivariate repeated measures techniques were used. Covariates included pretreatment stem height and diameter. More specific treatment comparisons were made using polynomial contrasts, and Bonferroni multiple comparison techniques.

TABLE VII. Analysis of variance F-values for effects of ozone(O3)/acid fog(AF) on ponderosa pine needle dry weight.

Source of variation	df	F-value
Model	53	2.22
O3 Trt[1]	2	13.40*
O3 CH(O3 Trt)	6	1.74
AF Trt[2]	2	0.28
AF CH(AF Trt)	3	1.34
O3 Trt*AF Trt[3]	4	2.05
O3CH*AFCH(O3 Trt*AF Trt)	36	1.17
Error[4]	123	0.076

* F-values significant at 0.01

1 Test of hypothesis using the Ozone chamber(Ozone treatment) mean square as the error term.

2 Test of hypothesis using the AcidFog chamber(AcidFog treatment) mean square as the error term.

3 Test of hypothesis using the ozone chamber*acidfog chamber(ozone treatment*acidfog treatment) mean square as the error term.

4 Mean square error from the analysis of variance.

RESULTS:

The study began in June 1986 with ozone exposures followed by acid fog exposures which began in March 1987. SO_2 exposures began in January, 1986 and were completed April 13, 1987. Final assessment of growth alterations from the various exposure scenarios was not completed until September 1987 in order to fully assess the second year's growth resulting from the previous season's exposures.

The study was repeated a second year with ozone exposures of an equivalent population of seedlings of each of the 5 species beginning June 1987 and concluding in October 1987, and followed by acid fog exposures from December 1987 until April 1988. SO_2 exposures began in December 1987 and continued until April 1988. Bud elongation and final assessment of growth variables began in April 1988 and were not completed until September 1988.

Seedling Growth Response

Table VIII presents a compilation of all significant ($P<0.1$) treatment effects on growth observed in each of the 5 species after one year (1986-1987) of seasonal exposure to the three scenarios. Briefly, all species exhibited growth over time in all measured variables, e.g. increase in height and diameter over the year; and bud growth the following spring. Certain growth variables were significantly altered with one or all exposure scenarios (Table VIII). This alteration was, in most instances, a reduction compared to control treatments, but there were several instances of growth increases in some variables, especially with winter SO_2 exposure or acidic fog exposure (Table VIII).

Repeated Measures of height and diameter: Only western hemlock exhibited significant reductions in growth rate of height ($P<.05$) and diameter ($P<.025$) during exposure to ozone and acid fog. The growth rate slowed sooner in seedlings exposed to the higher ozone regime compared to charcoal-filtered air controls or the lower ozone concentration regime (Fig. 4). At the final harvest, the hemlock seedlings exposed to ozone/acid fog were reduced 10% in height compared to controls. Redcedar was also significantly effected by the ozone/acid fog exposure scenarios. However, an increase in the rate of height growth ($P<.10$) was seen with exposure (Fig. 4), and at final harvest the height of exposed seedlings was 8-12% increased over controls. The only other species exhibiting alterations in height or diameter with ozone/acid fog exposure was ponderosa pine, but this was not seen until the following spring in the second season of growth. A 10% reduction in height and diameter ($P<.05$) compared to controls was exhibited. No acid fog ozone interaction was observed.

Bud elongation in the spring/summer following the ozone/acid fog exposure period (June 86-April 87) was a 'repeated measure' on the same plants beginning with bud break during the spring and continued until it was judged that elongation of the bud was complete and/or next season's bud was set. Bud elongation rate was reduced in western hemlock ($P=.06$) and ponderosa pine ($p=.06$) with both levels of ozone (Fig. 5). Acidic fog at pH 2.1 also reduced bud growth in hemlock ($P=.09$), but not any other species (Fig. 6). On the other hand, western redcedar exhibited increased bud elongation rate with the highest ozone level ($P<.005$) and with acidic fog of pH 2.1 ($P<.05$) compared to controls (Fig. 6). Only Douglas-fir bud elongation was unaffected by ozone/acid fog exposures. Winter SO_2 exposure caused significant increases in bud elongation in all species except lodgepole pine, which

exhibited an increase in stem dry weight (Table VIII, Fig. 7). The fastest growth rate and the resultant increased bud length did not necessarily result from exposure to the highest SO_2 concentration in all species. In the case of western redcedar, the fastest growth rate was observed in the seedlings exposed to the lowest SO_2 concentration (B*0.67).

Final Biomass Harvest: Measures of biomass after spring growth following the previous year's exposures showed significant growth changes in all species, but the extent of the damage was notably different between the 5 species. Ponderosa pine (P=.05), hemlock (P=.05) and Douglas-fir (P=.10 -.15) all exhibited significant reductions in needle (total and certain age classes), stem and root dry weight with ozone and acid fog exposure. Table IX illustrates percent changes in these variables compared to charcoal-filtered air controls as a result of the two ozone treatment levels. In addition to these ozone main treatment effects with the ozone/acid fog exposure scenario, acid fog main treatment effects were observed in Douglas-fir as reduction in biomass of current year needles (P=.05); and in hemlock significant reductions in bud elongation (P=.09) and root/needle dry weight ratio (P=.10) were noted (Table X). Western redcedar, unlike the other species, exhibited significant increases in growth variables as ozone treatment effects (Table IX), acid fog effects (Table X), and ozone-acid fog interactions. Only root dry weight was reduced significantly below controls with exposure (Table IX, X). Lodgepole pine biomass was apparently not significantly affected with exposure to ozone and acid fog.

The study was repeated with the identical treatment levels of all 3 exposure scenarios beginning June 1987 and continued through October 1988 for final assessments of growth. The growth alterations observed were similar in this exposure season, with ponderosa pine exhibiting the largest number of growth measures altered with ozone/acid fog exposure, including reductions in stem, needle and root biomass, and diameter, but unlike the previous year, a slight increase in spring bud growth with the lower ozone treatment. Western redcedar again showed the least susceptibility to the exposure regimes. Unlike the previous year, lodgepole pine exhibited significant alterations in growth measures as a result of the ozone exposure, including reductions in root and needle biomass. Acid fog exposures and the SO_2 exposures, as with the 1986-1987 exposures, caused significant increases in bud elongation the following spring and, unlike the previous year, increases in needle biomass.

DISCUSSION:

Alterations in any of the growth variables, either during or following the exposure periods, are the criteria for assessing relative sensitivity among the 5 species. Based simply on the number of growth measures reduced by one season's exposure, ponderosa pine and hemlock are somewhat more responsive to the ozone/acid fog deposition scenario than the other three species, with lodgepole pine being the least responsive. Some species

exhibited increases in one or several measures of growth with exposure. Western redcedar exhibited significant increases rather than decreases in a number of the growth variables as a result of ozone/acid fog exposures, including the following spring's bud elongation. Hemlock and redcedar appeared to be more responsive to acid fog at both pH 3.1 and 2.1 than the other species. In addition, only these two species exhibited any visible needle injury to the fog exposures. The scenario of acid fog alone was assessed in just two of the species, both of which exhibited increases in height as a result. Douglas-fir also showed increases in stem diameter and stem dry weight, but reduction in root dry weight with pH 2.1. Exposure to SO_2 during the winter months, like the acid fog only exposures, appeared to cause increases in several growth variables. The most prevalent was an increase in spring bud elongation. It is important to note that most growth effects with treatment, in particular changes in biomass, did not occur during the time period of the exposure, but rather at the end of the following spring/summer bud elongation period. If growth had been monitored only during the period of exposure, the resultant alterations in growth from the ozone/acid fog treatment would not have been detected. It is interesting to note that, at least from one years' exposure results, reduction in spring bud elongation occurs with ozone/acid fog exposures, and increases in rate and length occurs with winter SO_2 exposures in all the species screened but one, lodgepole pine. This measure of spring bud elongation rate and final length attained is perhaps reflective of the impact of the particular deposition scenario on carbohydrate reserves accumulated in the bud during the ozone/acid fog exposure period, and the role these revserves play in growth of the bud the following spring. It is important to remember that the observations reported here are from the first season's exposures, and only general reference to the second exposure season's responses are reported.

The two exposure studies ('86-87 & '87-88), however, are in general agreement regarding reductions in biomass of various tissue components of the seedlings following spring growth. Based on these growth responses to the particular deposition scenarios, ponderosa pine appears to be the most susceptible conifer to ozone/acid fog exposures, and western redcedar and lodgepole pine the least susceptible. Douglas-fir and western hemlock were intermediate in response. Acidic fog exposures alone, and winter SO_2 exposures were both notable in causing a number of growth measures to be increased above controls. None of the biomass measures for any of the species exhibited any reductions greater than 10% with these exposure scenarios. However, there were increases in biomass of needles, stem and spring bud elongation from 7-30% above controls in all of the species.
The increases in needle and stem biomass and the reduced or unchanged root biomass with acidic fog or SO_2 exposure result in reduced root/shoot ratios in hemlock, ponderosa pine and Douglas fir. This imbalance in allocation may have a detrimental effect on growth and seedling establishment with continued multi-year exposures. With only one year of exposure, however, speculation

seems premature. The cause of this increase in biomass and bud elongation and the resultant consequences of this altered root/shoot ratio is under study.

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10. The mention of trade names or commercial products does not constitute endorsement by the U.S. EPA.

FIGURE 1. Simulated exposure regime for acid fog giving duration and frequency of events over a 60-day period.

FIGURE 2. Simulated exposure regimes for ozone. The 'BASE' regime was employed only in the '87-88 exposure season. The 30-day regimes were repeated over the 134 day ('86-87 season) and 126-day ('87-88 season) exposure period.

FIGURE 3. Simulated exposure regimes for SO_2. The 60-day exposure regimes were repeated over the 90-day exposure periods during the fall and winter months of '86-87 and '87-88.

FIGURE 4. Changes in height and diameter of western hemlock and western redcedar over the 134-day ozone exposure period of the ozone/acid fog exposure scenario ('86-87 season). The average standard errors for western hemlock diameter: Control = 1.006; Base*1.6 = 1.006; Base*1.8 = 1.006; height: Control = 1.006, Base*1.6 = 1.006, Base = 1.006. For western redcedar diameter: Control = 1.012, Base*1.6 = 1.012, Base*1.8 = 1.012; Height: Control = 1.011, Base*1.6 = 1.012, Base*1.8 = 1.011.

FIGURE 5. Spring bud elongation following ozone and acid fog exposure. The plots reflect the average ozone effect over all fog treatments. Average standard errors for ponderosa pine were Control = 1.617, Base*1.6 = 1.475, Base*1.8 = 1.507; for Douglas-fir Control = 1.872, Base*1.6 = 2.268, Base*1.8 = 1.877; for western hemlock Control = 2.614, Base*1.6 = 1.916; Base*1.8 = 3.3422; for western redcedar Control = 1.133, Base*1.6 = 1.096, Base*1.8 = 1.114. Control is charcoal-filtered air.

FIGURE 6. Spring bud elongation following ozone and acid fog exposure scenario. The plots reflect the average fog effect over all ozone treatments. Average standard error for western hemlock were pH 5.6 = 2.630, pH 3.1 = 2.672, pH 2.1 = 2.676; for western redcedar pH 5.6 = 1.116, pH 3.1 = 1.119, pH 2.1 = 1.116.

FIGURE 7. Spring bud elongation as affected by 90-day SO_2 exposure. Average standard errors for ponderosa pine were Control = 1.053, Base = 1.053, Base*0.67 = 1.053, Base*0.33 = 1.053; Douglas-fir Control = 1.208, Base = 1.209, Base*0.67 = 1.205, Base*0.33 = 1.214; western hemlock Control = 1.112, Base = 1.115, Base*0.67 = 1.113, Base*0.33 = 1.112. Control is charcoal-filtered air.

Fig. 1

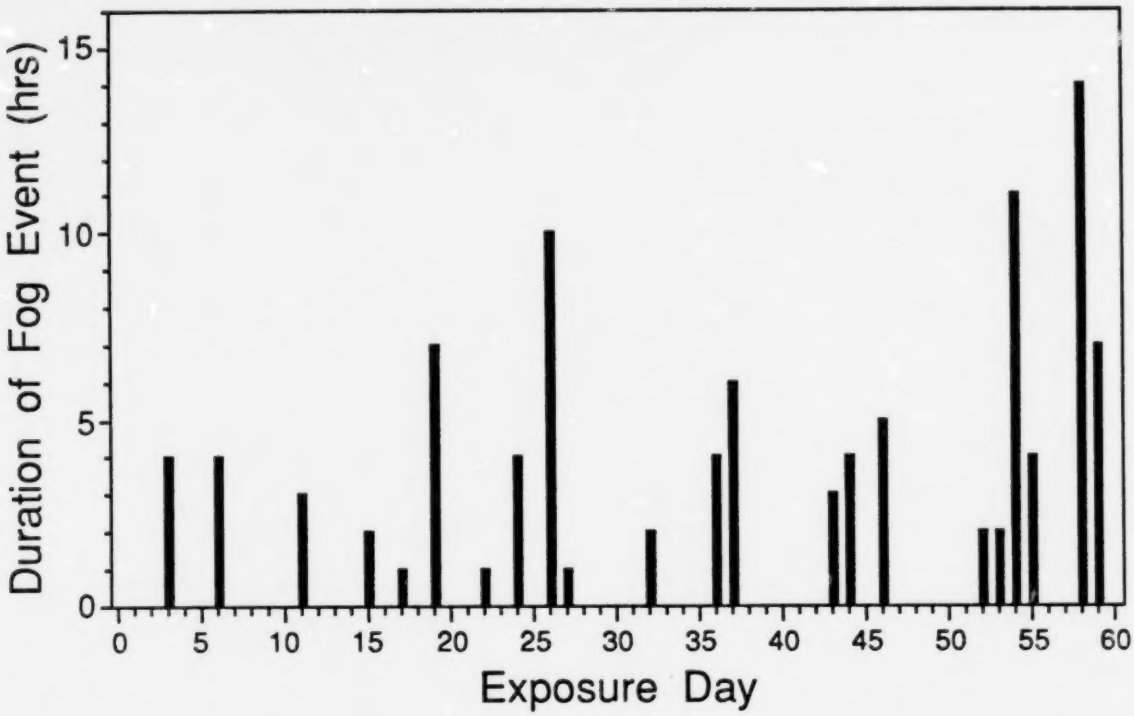
Duration of Fog Event (hrs)
0
5
10
15
0
5
10
15
20
25
30
35
40
45
50
55
60
Exposure Day

FIG. 2

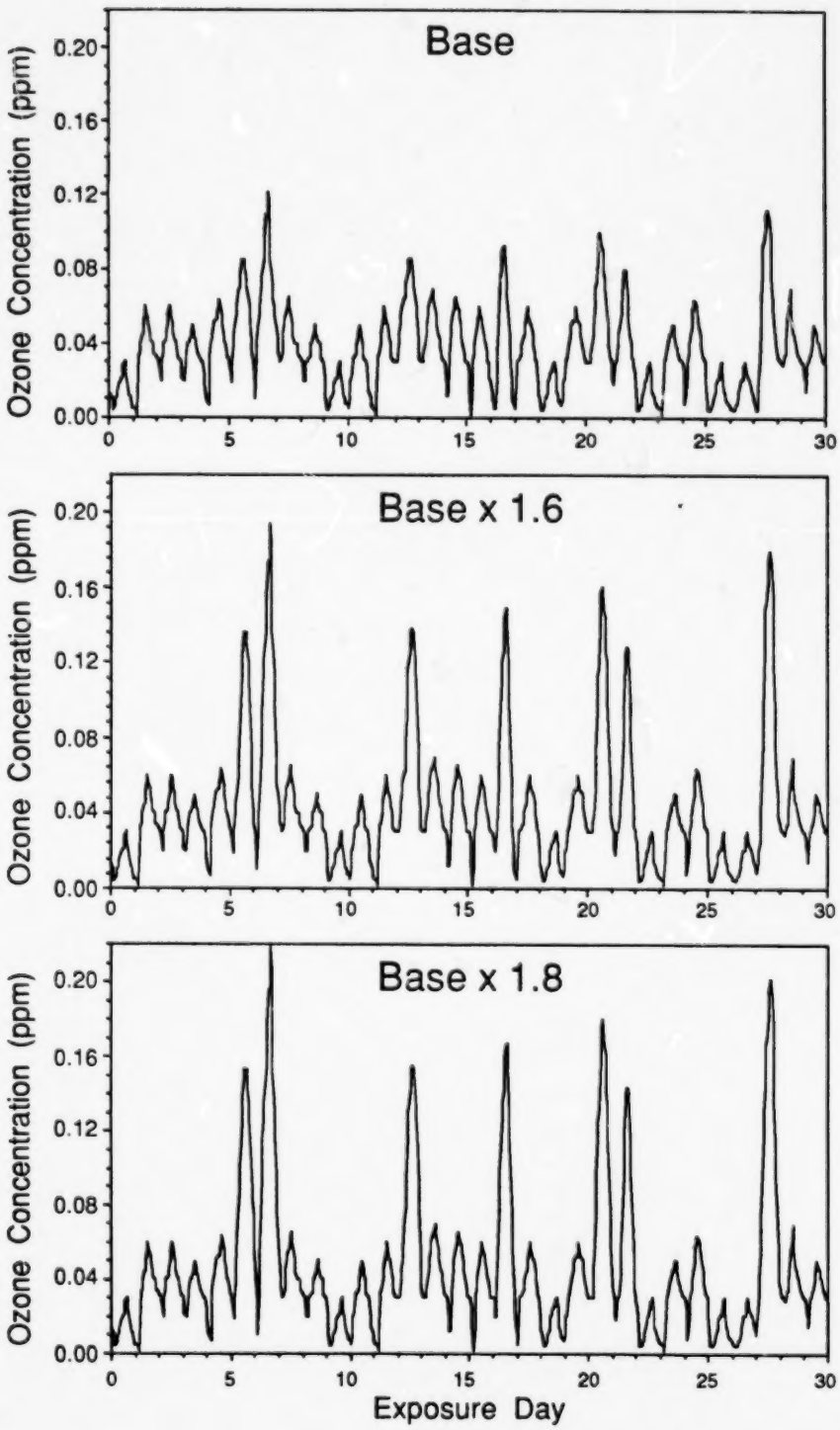
Base
Base x 1.6
Base x 1.8
Ozone Concentration (ppm)
0.00
0.04
0.08
0.12
0.16
0.20
0
5
10
15
20
25
30
Exposure Day

FIG. 3

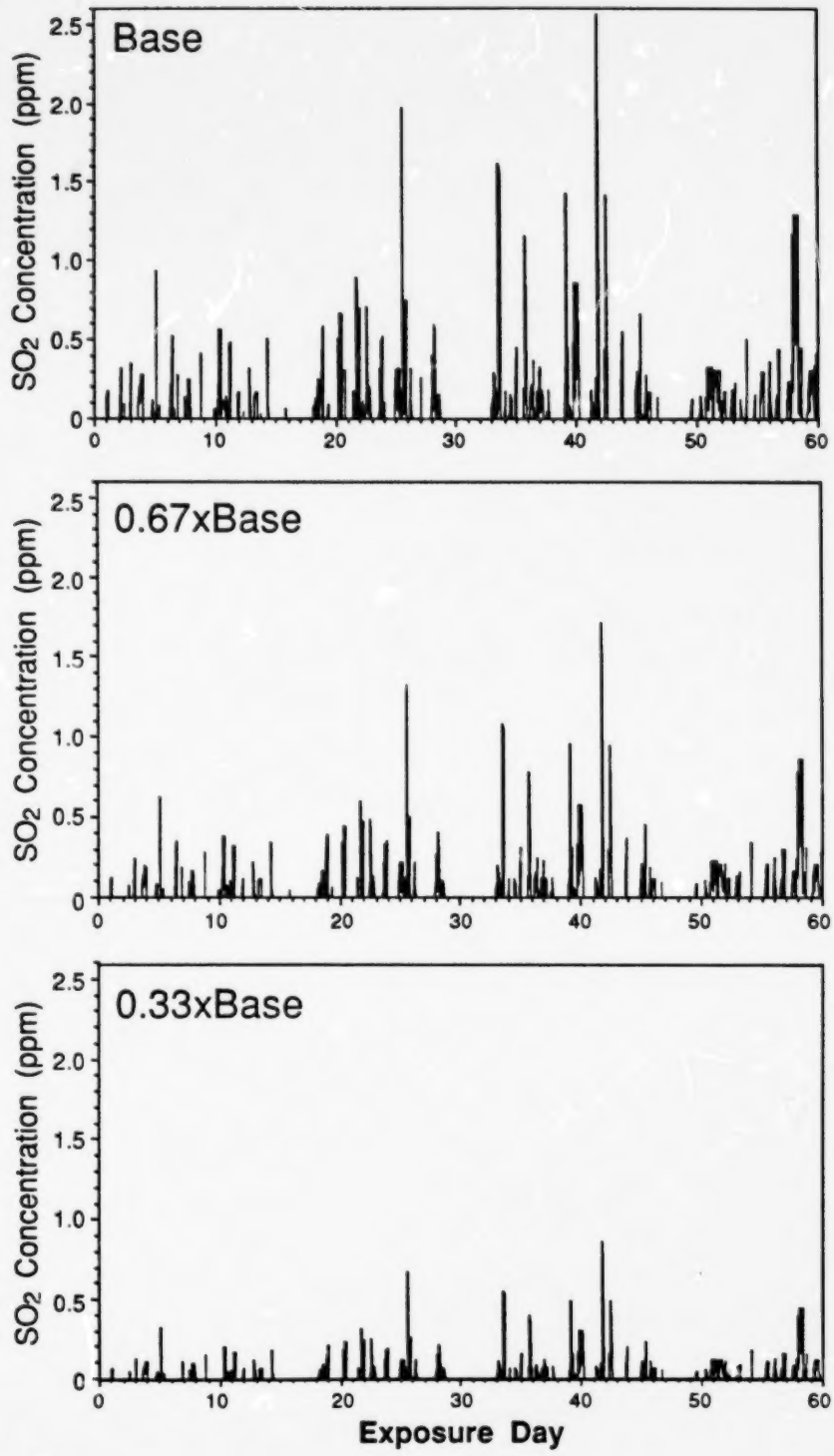
Base
0.67xBase
0.33xBase
SO_2 Concentration (ppm)
0
0.5
1.0
1.5
2.0
2.5
0
10
20
30
40
50
60
Exposure Day

FIG. 4

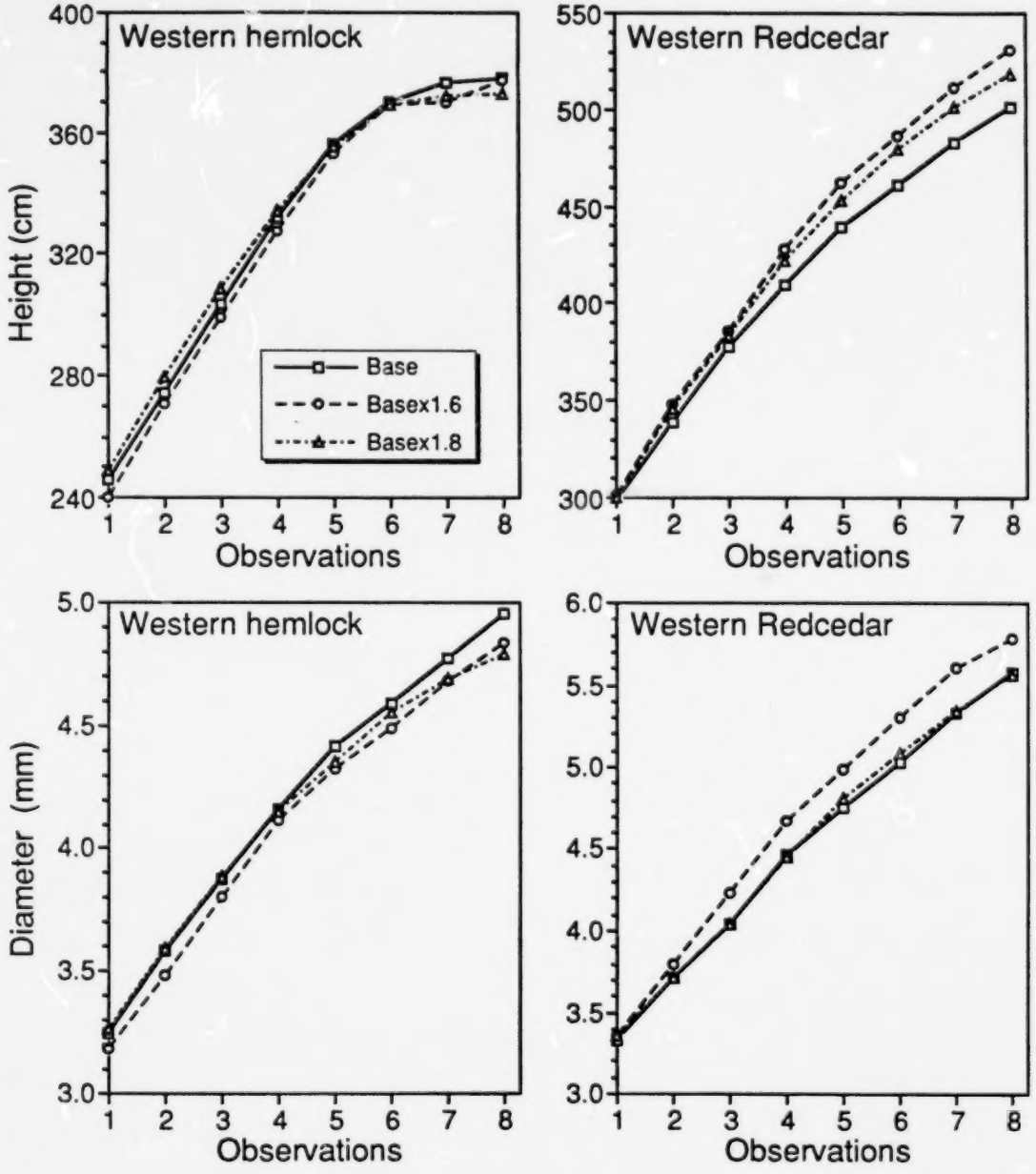
Western hemlock
Height (cm)
400
360
320
280
240
Base
Basex1.6
Basex1.8
1 2 3 4 5 6 7 8
Observations
Western Redcedar
550
500
450
400
350
300
1 2 3 4 5 6 7 8
Observations
Western hemlock
Diameter (mm)
5.0
4.5
4.0
3.5
3.0
1 2 3 4 5 6 7 8
Observations
Western Redcedar
6.0
5.5
5.0
4.5
4.0
3.5
3.0
1 2 3 4 5 6 7 8
Observations

FIG. 5

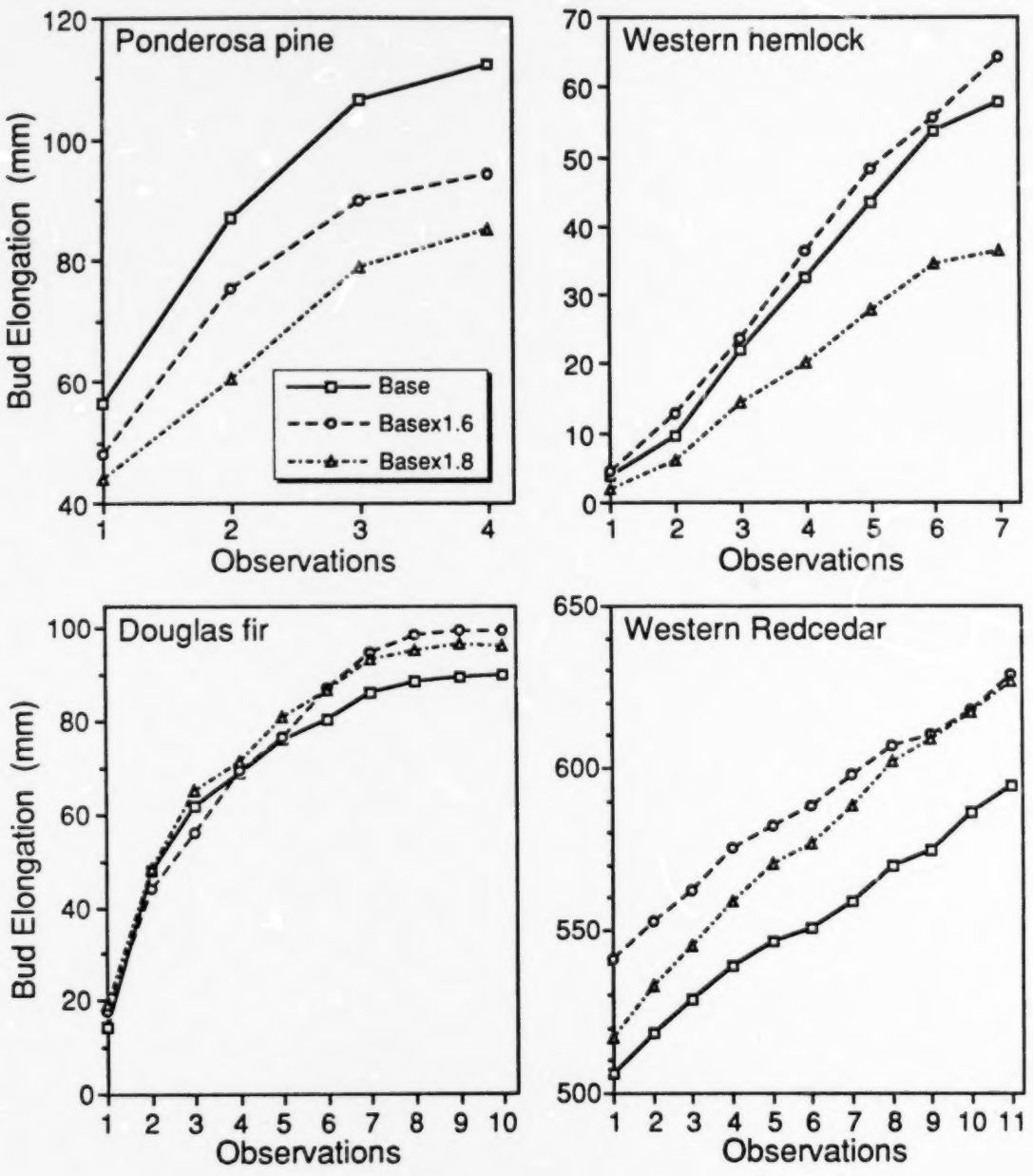
Ponderosa pine
Bud Elongation (mm)
Observations
Base
Basex1.6
Basex1.8
Western hemlock
Observations
Douglas fir
Bud Elongation (mm)
Observations
Western Redcedar
Observations

FIG. 6

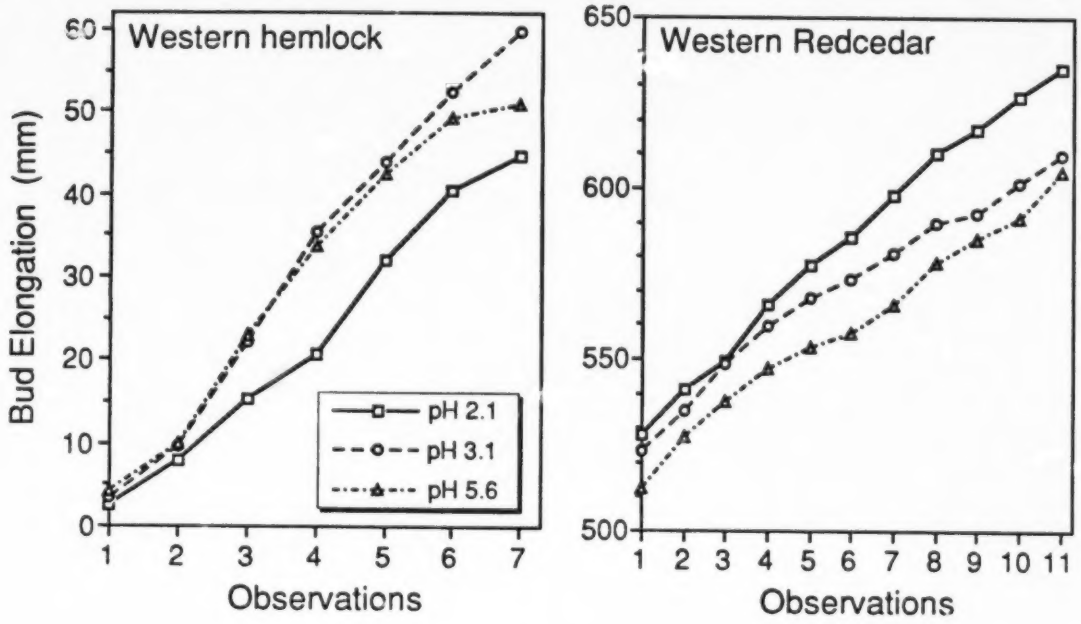
Western hemlock
Bud Elongation (mm)
0
10
20
30
40
50
60
1
2
3
4
5
6
7
Observations
pH 2.1
pH 3.1
pH 5.6
Western Redcedar
500
550
600
650
1
2
3
4
5
6
7
8
9
10
11
Observations

FIG. 7

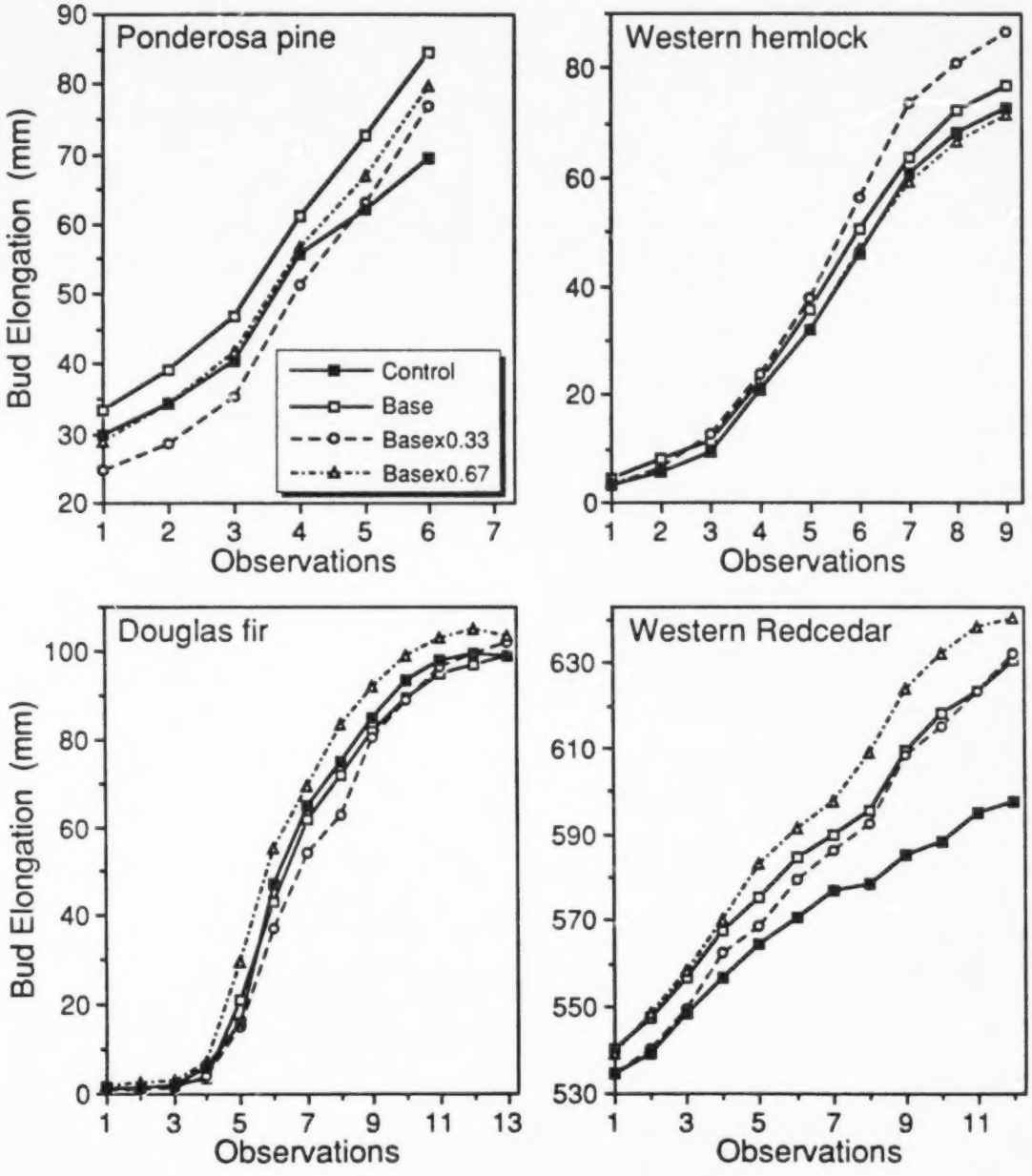
Ponderosa pine
Western hemlock
Douglas fir
Western Redcedar
Bud Elongation (mm)
Observations
Control
Base
Basex0.33
Basex0.67

TABLE IV. Ozone/Acid Fog exposure scenrario for the '86-87 exposure season with elements of design and measurements taken.

TIME PERIOD	DURATION (days)	POLLUTANT	DESIGN	TREATMENT	MEASUREMENTS
03/01/86 - 06/10/86	----------			Nursery Site	Seedling Selection
06/10/86 - 10/17/86	134	Ozone	3 chambers/ treatment 20 seedlings/ species/chamber	C 67 71 7-hr means (ppb)	Pretreatment Harvest (40 seedlings) Repeated measures Visible injury (4x)
10/17/86 - 03/01/87	----------			Seedlings held in open-tops Seedlings from each chamber	
03/01/87 - 05/01/87	60	Acid Fog	2 chambers/ treatment 10 seedlings/ species/chamber	pH 5.6 pH 3.1 pH 2.1	Initial measurements Repeated measures Visible injury (2x)
04/12/87 -					Bud elongation measurements
05/01/87 - 09/15/87	----------			Nursery Site	Repeated measures Bud elongation only
7/14 (Douglas Fir) 9/03 (Ponderosa pine) 9/12-9/15 (Western hemlock, Western redcedar, Lodgepole pine)	----------			Final Harvest	Destructive harvests of all seedlings for biomass, stem height, diameter, terminal Visible injury bud length

TABLE V. Acid Fog Exposure Schedule for the '86-87 exposure season with elements of design and the measurements taken.

TIME PERIOD	DURATION (days)	POLLUTANT	DESIGN	TREATMENT	MEASUREMENTS
03/01/86 - 03/01/87	----------			Nursery Site	Seedling Selection
03/01/87 - 05/01/87	61	Acid Fog	2 chambers/tmt 20 seedlings/ species/chamber	pH 5.6 pH 3.1 pH2.1	Pretreatment Biomass Harvest (40 seedlings) Pretreatment measures (ht, dia.) Visible injury (day 50 & 85) Final Measures (ht., dia.,)
05/01/87 - 09/22/87	----------			Nursery Site	
05/20/87					Visible injury Repeated Measures terminal bud elongation
8/17 (Ponderosa pine) 9/22 (Douglas fir)				Final Harvest	Destructive Harvest of all for biomass, final height, stem diameter, & bud length Visible injury

TABLE VI. SO_2 Exposure Schedule for the '86-87 exposure season with elements of design and the measurements taken.

TIME PERIOD	DURATION (days)	POLLUTANT	DESIGN	TREATMENT	MEASUREMENTS
03/01/86 - 01/01/87	----------			Nursery Site	
					Seedling Selection
01/13/87 - 04/13/87	90	SO_2	2 chambers/tmt 20 seedlings/ species/chamber	C Base B*.67 B*.33	Pretreatment Biomass Harvest (40 seedlings) Pretreatment measures (ht, dia.) Visible injury (day 50 & 85) Final Measures (ht., dia.,)
04/13/87 - 09/15/87	----------			Nursery Site	
05/13/87					Visible injury Repeated Measures terminal bud elongation
8/10 (Douglas fir) 9/09 (Ponderosa pine) 9/17 (Western Hemlock, Lodgepole pine) 9/29 (Western Redcedar)				Final Harvest	Destructive Harvest of all for biomass, final height, stem diameter, & bud length

TABLE VIII. Summary of exposure treatment effects with three different scenarios over one year. The listing of a variable indicates a significant reduction with at least one of the treatment levels from control treatment ($P<0.1$) unless noted as "!", which indicates a significant increase above control ($P<0.1$).

SPECIES	OZONE + ACID FOG				ACID FOG ONLY	SO_2
	OZONE TREATMENT EFFECT		ACID FOG EFFECT	OZONE X ACID FOG		
	Repeated Measures	Final Biomass *	Final Biomass	Final Biomass	Final Harvest	Final Harvest
Ponderosa pine	bud **	ht.,dia, NDW, 2NW, 2NC, SDW, RDW	-	-	ht!, R/N	bud!, 2NC
Douglas-fir	-	NDW, 1NW, 3NW	3NW	-	ht!,dia!, SDW!, RDW	bud!, dia 2NW, 2NC
Western hemlock	ht,dia, bud	ht, NDW, SDW, RDW	bud R/N	-	NA	bud! RDW R/N
Western redcedar	bud!, ht!	ht!	bud!, NDW!, SDW! RDW, R/N	R/N	NA	bud!, ht!
Lodgepole pine	bud	-	-	-	NA	SDW!

* - measurements taken after bud elongation in the spring/summer following the exposure periods (ozone: May-Oct.; acid fog: Feb.-Apr.; SO_2: Feb-Apr.)

** - bud = spring bud elongation rate or the final length of apical bud after spring elongation
ht. = stem height
dia. = stem diameter
NDW = needle dry weight
SDW = stem dry weight
RDW = root dry weight
R/N = root/needle dry weight ratio
xNW = needle dry weight by age class (x=1,2,or 3)
xNC = needle number by age class (x=1,2 or 3)
NA = species not included in treatment

TABLE IX. Changes in biomass after spring growth following previous year's exposures to ozone/acid fog. Alterations due to acidic fog averaged over all ozone treatments and reported as percent difference from pH 5.6 fog for an acid fog treatment effect. Significant at the level of .05 is marked (*) from multiple comparison Bonferroni test.

SPECIES	NEEDLE DRY WEIGHT		STEM DRY WEIGHT		ROOT DRY WEIGHT		ROOT/NEEDLE RATIO	
	pH 3.1	pH 2.1	pH 3.1	pH 2.1	pH 3.1	pH 2.1	pH 3.1	pH 2.1
Ponderosa pine	+ 4.6	+ 2.4	+ 3.8	- 1.0	+ 1.0	- 5.0	- 4.5	- 8.0
Douglas fir	+10.0	+ 1.6	+ 9.8	+ 2.3	+ 6.3	-12.5	- 4.1	-14.2
Western Hemlock	0	+ 2.0	+ 2.8	+ 4.7	-17.0	-22.0	-17.0	-24.0 *
Western Redcedar	+ 6.0	+10.1	+ 6.0	+11.6	- 6.2	-20.2 *	-14.8	-30.2
Lodgepole pine	+ 4.0	+16.0	+ 4.0	+ 1.0	+ 3.8	- 3.1	0	-19.5

TABLE X. Changes in biomass after spring growth following previous year's exposures to ozone/acid fog. Alterations due to ozone averaged over all fog treatments and reported as percent difference from charcoal-filtered control. Significantly different from charcoal-filtered control in Bonferroni T test at 0.05 level is marked (*).

SPECIES	NEEDLE DRY WEIGHT		STEM DRY WEIGHT		ROOT DRY WEIGHT		ROOT/NEEDLE RATIO	
	High O3	Low O3	High O3	Low O3	High O3	Low O3	High O3	Low O3
Ponderosa pine	-33.6 *	-27.3 *	-36.3 *	-20.8 *	-43.6 *	-33.0 *	- 9.3	- 5.2
Douglas fir	-19.2	-18.1	-14.8	-14.4	-20.5	-17.6	- 2.4	1.6
Western hemlock	-11.0 *	- 4.5	-20.5 *	1.0	-29.8 *	- 2.6	- 4.9	1.9
Western redcedar	- 3.0	+10.1	+ 8.0	+12.0	-14.6	- 1.0	-14.7	-11.1
Lodgepole pine	+ 9.0	-11.0	+14.0	+ 3.0	- 6.1	- 9.8	-15.5	+ 1.2